

THE SHAPE OF LONG OUTBURSTS IN U GEM TYPE DWARF NOVAE FROM AAVSO DATA

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ABSTRACT

We search the American Association of Variable Star Observers (AAVSO) archives of the two best studied dwarf novae in an attempt to find light curves for long outbursts that are extremely well-characterized. The systems are U Gem and SS Cyg. Our goal is to search for embedded precursors such as those that have been found recently in the high fidelity *Kepler* data for superoutbursts of some members of the SU UMa subclass of dwarf novae. For the vast majority of AAVSO data, the combination of low data cadence and large errors associated with individual measurements precludes one from making any strong statement about the shape of the long outbursts. However, for a small number of outbursts, extensive long term monitoring with digital photometry yields high fidelity light curves. We report the discovery of embedded precursors in two of three candidate long outbursts. *This is the first time that such embedded precursors have been found in dwarf novae above the period gap*, and reinforces van Paradijs’ finding that long outbursts in dwarf novae above the period gap and superoutbursts in systems below the period gap constitute a unified class. The thermal-tidal instability to account for superoutbursts in the SU UMa stars predicts embedded precursors only for short orbital period dwarf novae, therefore the presence of embedded precursors in long orbital period systems – U Gem and SS Cyg – argues for a more general mechanism to explain long outbursts.

Subject headings: accretion, accretion disks — binaries: close — binaries: general — novae, cataclysmic variables — methods: observational — stars: dwarf novae

1. INTRODUCTION

Kepler observations of short orbital period dwarf novae (below the “period gap”) have given us for the first time clear evidence for the presence of embedded precursors, or “failed” outbursts, at the beginning of superoutbursts of SU UMa systems (Cannizzo et al. 2012). This behavior had been partially seen before in some systems with fragmentary data, but is now quite clear. Thanks to the high fidelity AAVSO data of the past ~ 10 yrs, we report the discovery of such precursors also in two systems *above* the period gap. This may have consequences for theoretical models for the long outbursts and the superoutbursts.

Cataclysmic variables (CVs – Warner 1995ab) are semi-detached interacting binaries containing a Roche-lobe filling K or M secondary that transfers matter to a white dwarf (WD). CVs show a “gap” between $P_h \sim 2$ and 3 (where $P_h = P_{\text{orbital}}/1$ hr) during which time the secondary star loses contact with its Roche lobe and mass transfer ceases as the systems evolve to shorter orbital periods. Thus at $P_h \simeq 3$ the binary becomes fully detached. At $P_h \simeq 2$ the secondary comes back into contact with its Roche lobe and mass transfer resumes. Systems can also be “born” in the gap, so it is not completely empty. For $P_h \lesssim 2$ angular momentum loss from the binary is thought to be due solely to gravitational radiation. The CV subclass of dwarf novae (DNe) also have semi-periodic outbursts. SU UMa stars are DNe below the period gap exhibiting short, normal outbursts (NOs) and superoutbursts (SOs). SOs show superhumps which are modulations in the light curve at periods slightly exceeding the orbital period; superhumps are the defining property of SOs.

DNe outbursts are thought to be due to a thermal limit cycle accretion disk instability (Smak 1984) in which material

is accumulated in quiescence and then dumped onto the WD during outburst. During short outbursts in longer period DNe, a few percent of the stored mass is accreted, and during long outbursts a significant fraction ~ 0.2 of the stored mass is accreted. For the SU UMa stars, a SO is thought to accrete $\gtrsim 0.7 - 0.8$ of the stored mass. Although the accretion disk is never in steady state during the limit cycle, it is close to steady state during long outbursts.

U Gem and SS Cyg are the two DNe with the most complete AAVSO coverage. U Gem ($P_h = 4.25$) was discovered by John Russell Hind in 1855 (Hind 1856), and SS Cyg ($P_h = 6.60$) by Louisa D. Wells in 1896 (Wells 1896). To date, U Gem has $\gtrsim 115,000$ observations, and SS Cyg has $\gtrsim 455,000$. Figure 1 shows the number of individual observations n_{obs} for each 24 hr interval versus time for each long term light curve.

Recent observations by *Kepler* have revealed details of the outburst behavior that have been partially seen previously³, but which can now be studied in much greater detail (Cannizzo et al. 2012). Of particular interest for this work is the presence of an embedded “failed” NO at the start of a SO. Within the context of the thermal-tidal instability (TTI) model for SOs (Osaki 1989; Ichikawa & Osaki 1992; Osaki 2005, see his Figures 3 and 4), embedded precursors are understood as being due to a temporary squeezing of the outer accretion disk by increased effective tidal forces due to the onset of a tidal instability. This instability drives the outer disk between circular and eccentric shapes when the outer edge of the disk expands beyond the point of 3:1 resonance with the binary orbital period, i.e., the point at which $2\pi/\Omega$ around the WD equals $P_{\text{orbital}}/3$ (Whitehurst 1988). The discovery of the tidal instability by Whitehurst led Osaki to propose the TTI, which combines the accretion disk thermal limit cycle instability with the tidal instability. A necessary condition for the

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³ For example, Figure 3.36 from Warner (1995b) shows precursors of varying depths in SOs of VW Hyi, but the light curves are smoothed, filled versions based on fragmentary data.

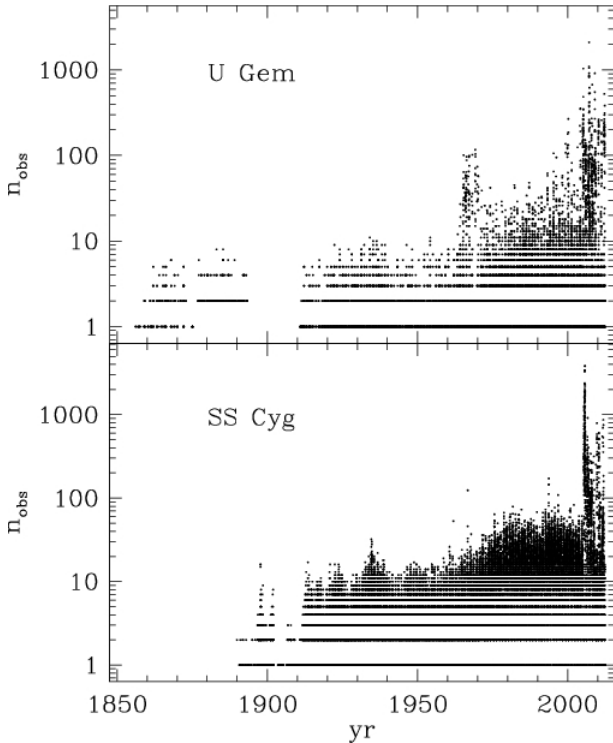


FIG. 1.— The number of observations entering into a daily mean n_{obs} for the historical AAVSO light curves of U Gem (top panel) and SS Cyg (bottom panel).

tidal instability is that the mass ratio $q \equiv M_2/M_1 < 0.25$ so that for long outbursts, in which a substantial amount of matter is stored in the disk, the presence of high viscosity material can expand the outer disk radius beyond the 3:1 radius. Thus superhumps are seen only in short orbital period DNe.

An important point is that, if the TTI model only applies to low q binaries, and therefore only to short orbital period DNe, one expects it not to apply to systems longward of the period gap (since for Roche-lobe filling main-sequence donors, systems with $q \lesssim 0.25$ have $P_h \lesssim 2.5$ hr). Therefore, the presence of embedded precursors in systems above the period gap, should they exist, would argue for a more general physical mechanism for long outbursts in all DNe. Previous studies of DNe outbursts using amateur data have proved useful in delineating timescales and constraining models (e.g., Campbell & Shapley 1940, Sterne, Campbell & Shapley 1940, Bath & van Paradijs 1983, van Paradijs 1983, Szkody & Mattei 1984, Cannizzo & Mattei 1992, 1998, Ak, et al. 2002, Simon 2004). Van Paradijs (1983) studied a sample of DNe spanning the period gap and found that short outburst durations increase with orbital period, whereas long outburst durations are relatively constant with orbital period. He proposed that the relation of SOs to NOs for DNe below the period gap and of long outbursts to NOs for DNe above the period gap are equivalent; superoutbursts are, in his view, just long outbursts seen in short orbital period DNe. This finding was amplified by Ak et al. (2002) using a larger sample.

For completeness we note that there have been prior critical analyses of the TTI model, from both theoretical and observational perspectives. Schreiber et al. (2004) compare numerical time dependent models of the TTI with an alternative model – enhanced mass transfer (EMT) from the secondary star. Their arguments are somewhat general, however, and although they conclude in the end that the EMT is favored,

they note “we have not proven the EMT [model] to be correct nor the TTI [model] not to work.” Also, in a series of papers Smak (2009abcd) presents arguments against the standard interpretation of superhumps in the SU UMa stars as being due to a precessing, eccentric disk⁴. Thus from his perspective the entire physical basis for the TTI would be called into question. Smak also favors the EMT model. Cannizzo et al. (2012) study the long term *Kepler* light curves of two SU UMa stars and argue that the tendency of recurrence times for normal outbursts to exhibit sometimes a local maximum half way between two superoutbursts argues against the TTI model, wherein one expects a monotonically increasing series of recurrence times between two superoutbursts (Ichikawa, Hirose, & Osaki 1993, see their Figure 1; Osaki 2005, see his Figure 3).

2. HIGH FIDELITY LONG OUTBURSTS IN U GEM AND SS CYG

Figure 1 shows the number of individual observations n_{obs} for each 24 hr interval within the historical AAVSO light curves for U Gem and SS Cyg. Data prior to 2000 are mainly visual and the errors are too large to be usable for detecting subtle effects such as embedded precursors to outbursts.

One can see a period of faster-than-exponential growth in the upper envelope of n_{obs} versus time. For the vast majority of the data, the uncertainty in flux associated with an individual measurement produces a scatter in the light curve precludes any detailed study of the shape of the outburst. Historically, the majority of the data were from visual observations in which estimates of a given variable star brightness are carried out by comparison with nearby field stars. The precision for any given data point in this method is ~ 0.3 - 0.5 mag, and, given the varying color biases between different observers, a simple averaging of $m_V(t)$ values for outburst during times when n_{obs} is large does not guarantee a light curve with true physical fidelity.

In the last ~ 10 yr this situation has changed due to the increased use of digital photometry. This trend can be seen in Figure 1. The intervals with digital photometry generally are accompanied by times during which $n_{\text{obs}} \gtrsim 300 - 1000$, i.e., more than $\sim 300 - 1000$ observations within a 24 hr interval. By restricting our attention to long outbursts lying within these times of large n_{obs} during the last 10 yr, and furthermore restricting the data to digital V -band photometry only (so as to exclude the individual color biases inherent in the visual data), we may considerably reduce the vertical scatter in the outburst data. We note that the presence of high n_{obs} data is a necessary but not a sufficient ingredient. High n_{obs} values ($\gtrsim 300$) are indicative of the use of digital photometry, but there must also be a high cadence rate near outburst onset to have a reasonable chance of determining whether or not a failed, embedded outburst accompanies the outburst start.

We have made careful study of each long outburst in U Gem and SS Cyg since 2000 in an effort to identify outbursts that are sufficiently well sampled by digital photometric observations such that one may make a clear statement concerning the presence of an embedded precursor. There are two such outbursts in U Gem and one in SS Cyg. Figure 2 shows an enhanced view of the U Gem light curve containing the two

⁴ The most recent numerical simulations of an accretion disk subject to the 3:1 instability reveal a disk shape that alternates between eccentric and circular (Montgomery 2012ab), therefore it may be more difficult than previously thought to detect an (instantaneously) eccentric disk shape in an eclipsing system.

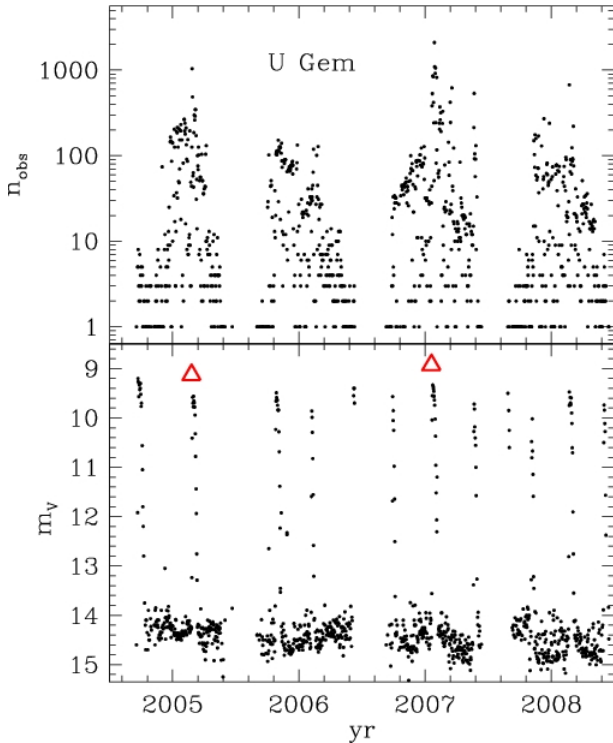


FIG. 2.— A portion of the U Gem long term light curve containing points for which n_{obs} is large. Shown are n_{obs} (top panel) and daily means for m_V (bottom panel). The small triangles (red) indicate the high fidelity long outbursts.

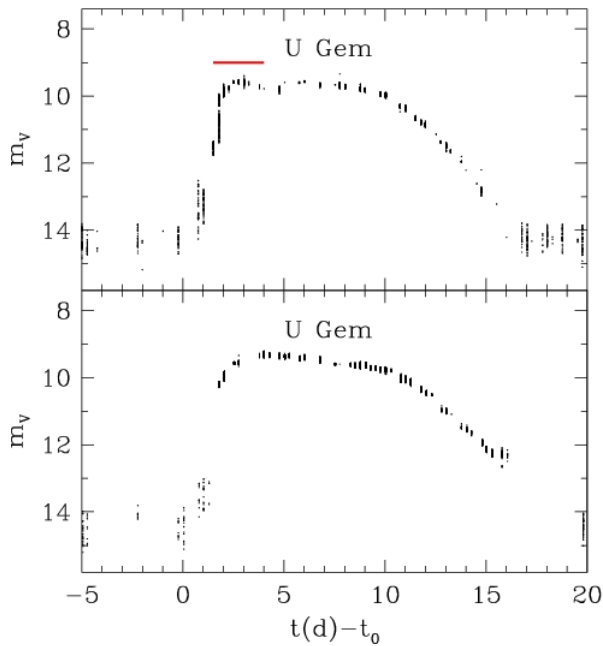


FIG. 3.— Detailed views for U Gem showing the first outburst of 2005 (top panel), for which $t_0 = 2005.15$, and the first outburst of 2007 (bottom panel), for which $t_0 = 2007.05$. Here we plot individual measurements rather than daily means. Only digital V -band photometry data are plotted. The horizontal bar (red) indicates the embedded precursor.

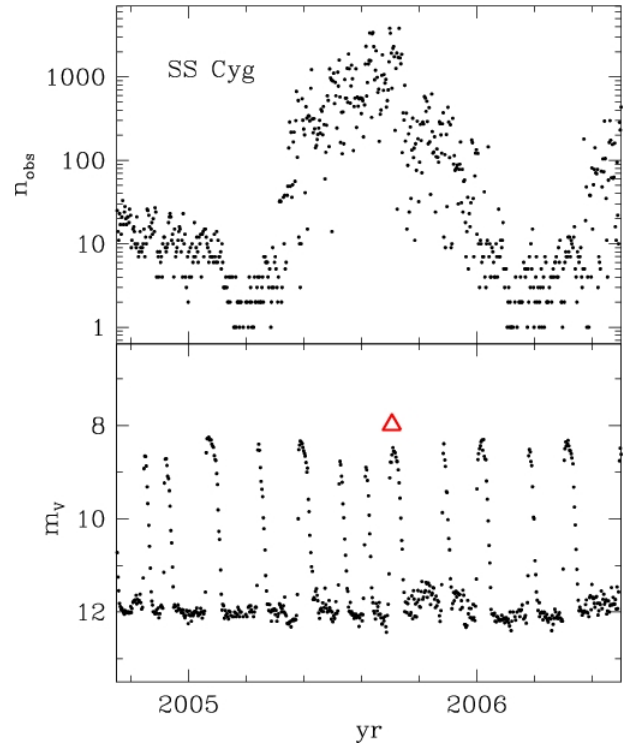


FIG. 4.— A detailed view for SS Cyg of the portion of the long term light curve containing points for which n_{obs} is large. Shown are n_{obs} (top panel) and daily means for m_V (bottom panel). The small triangle (red) indicates the high fidelity long outburst.

candidate long outbursts. The first outbursts of 2005 and 2007 are long and lie with regions of dense digital photometric coverage. Figure 3 shows detailed views of these two outbursts. The 2005 outburst shows an apparent failed outburst at the start, and the 2007 outburst does not. Figure 4 shows a stretch of $n_{\text{obs}} > 1000$ data for SS Cyg containing our one identified high fidelity long outburst, at ~ 2005.7 . It is shown in detail in Figure 5. It appears also to contain a failed outburst at the start. In summary, for two of the three long outbursts in the best studied DNe (both of which lie above the period gap) for which any statement can be made about the detailed shape of the outburst, there is an apparent failed, embedded outburst at the start, followed by a period of slow decay, followed by a period of faster decay. These three characteristics of long outbursts are the same as in the superoutbursts of the SU UMa stars, which lie below the period gap.

3. DISCUSSION AND CONCLUSION

By examining the best AAVSO data for U Gem and SS Cyg we have found evidence for embedded failed outbursts at the start of two out of three long outbursts for which such an exercise is feasible. These data are from digital photometry. For the 2005 U Gem outburst, the possibility of a time variable calibration to explain the embedded precursor seems unlikely since the light curve is comprised of data from several observers. For the 2005 SS Cyg outburst, the precursor stands out more strongly. For other data in the long term light curves, the quality is not good enough for one to be able to make any clear statement about the detailed outburst shape.

The thermal-tidal instability model was developed to account for the short orbital period SU UMa stars which have $q < 0.25$. Since CVs have Roche-lobe filling secondary stars, this constrains the secondary star mass to be $\sim 0.1 M_{\odot} P_h$, un-

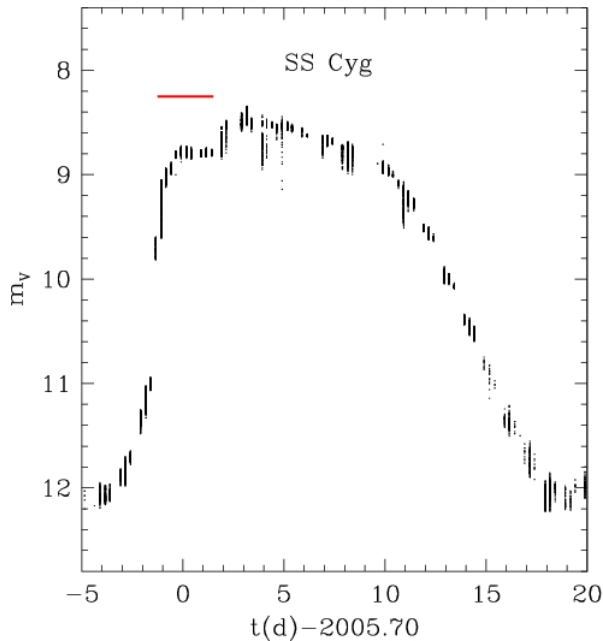


FIG. 5.— A detailed view of the high fidelity long outburst during late 2005 in SS Cyg, showing only digital V -band photometry. Individual measurements are shown, not daily means. The horizontal bar (red) indicates the embedded precursor.

less the star has been driven considerably out of thermal equilibrium due to mass loss. Therefore DNe above the period gap such as U Gem and SS Cyg with orbital periods between 4 and 7 hr cannot possibly satisfy $q < 0.25$ for $M_{WD} \simeq M_{\odot}$, and therefore the thermal-tidal model should not be a physical ingredient of their outbursts. Two of three long outbursts

in DNe longward of the period gap which have the requisite AAVSO data fidelity show (i) the initial failed outburst embedded at the start, (ii) the slow decay consistent with viscous decay, and (iii) the faster decay consistent with thermal decay. These three characteristics are also manifested in the long outbursts in DNe below the period gap — i.e., the superoutbursts in the SU UMa stars. Therefore Occam's razor would seem to demand a common explanation which does not depend on q . The only difference between the two types of outbursts is the presence of superhumps in the superoutbursts, thus the association of superhumps with superoutbursts appears to be associative rather than causal.

Finally, it is worth noting that U Gem exhibited an unusually long outburst in October 1985 with a duration of ~ 39 d (Cannizzo et al. 2002). The usual duration of long outbursts in U Gem is ~ 12 d. It is unclear how the existence of this long outburst impacts our conclusions. In the context of the standard accretion disk limit cycle for DN outbursts (Smak 1984), the cooling front responsible for terminating the flat-topped portion of a long outburst must have been prevented from propagating, perhaps due to an unusually large amount of stored disk mass. Cannizzo et al. (2002) determined a viscous decay time 26 ± 6 d mag^{-1} from the AAVSO light curve. Given that virtually all other long outburst decays in U Gem and SS Cyg do not last long enough for the decay slope to be measurable, this one long outburst gives us our only measure of the viscous time scale in a DN longward of the period gap.

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